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Hot Dry Rock: A Versatile Alternative Energy Technology

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Abstract

Hot dry rock (HDR) is the most abundant geothermal resource, and is found almost everywhere at depth. The technology to extract energy from HDR for practical use has been under development at the Los Alamos National Laboratory for more than twenty years. During the 1970's, the possibility of mining the heat from HDR by circulating water through an engineered geothermal reservoir was first demonstrated on a small scale. Between 1980 and 1986, a larger, deeper, and hotter HDR reservoir was constructed. This large reservoir was subsequently mated to a permanent surface plant. A number of flow tests of this large HDR reservoir were conducted between 1991 and 1995. The results of these tests have indicated that it should be practical to operate an HDR heat mining facility to produce power on a sustained basis.

An industry-led, government cost-shared project to produce and market energy generated from HDR is currently being put in place. That project should help demonstrate that HDR reservoirs can be operated to provide energy for long periods of time at rates sufficient to be commercially viable. In the longer run, additional applications of HDR technology such as water and waste treatment, and steam generation for oil field flooding may come into widespread use.

Introduction

One of the world's great untapped energy resources lies right beneath our ft in the form of hot dry rock (HDR), the common geologic condition at depth almost everywhere in the world. It has been estimated that there is enough heat in HDR at depths that can be reached with today's drilling technology to supply all the energy needs of the world for centuries to come[1]. Natural sources of steam and hot water have long been used to provide heat and generate electricity at numerous locations[2]. In fact, these hydrothermal energy resources, along with hydropower, are among the few non-fossil energy forms that have found widespread commercial application. Undoubtedly, the use of hydrothermal resources will continue to increase but hydrothermal areas are the exception rather than the rule and account for only a small and localized fraction of the world's store of geothermal energy. The real potential for growth in the use of geothermal energy lies in finding an economic way to mine the heat from the large, ubiquitous HDR resource.

HDR Heat Mining Technology. All recent heat mining work is based on a concept outlined in a patent issued to the Los Alamos National Laboratory in 1974[3]. That patent describes the formation of a fully-engineered geothermal reservoir in hot, crystalline rock by the application of hydraulic fracturing techniques, and the subsequent circulation of water through that engineered reservoir to mine the thermal energy from the hot rock. For more than two decades, the US Department of Energy (DOE) has sponsored work at Los Alamos directed toward developing heat mining technology to the point where extraction of the energy from HDR is practical and economic. Related HDR heat mining projects have been underway for a number of years in Japan[4] and western Europe[5], and an Australian HDR project is in its formative stages.

The HDR process is relatively simple: A well is drilled into hot, crystalline rock. Water is then injected at pressures high enough to open the natural joints in the rock. The water flows into the open joints and an engineered geothermal reservoir is thereby created. The reservoir consists of a relatively small amount of water dispersed in a large volume of hot rock. The relative dimensions and orientation of the reservoir are determined by the local geologic conditions, while its ultimate volume is a function of the injection pressures applied and the duration of the hydraulic fracturing operation. Seismic techniques are used to follow the growth of the reservoir and to assess its location and approximate dimensions[6]. Using the microseismic data as a guide, one or more additional wells are subsequently drilled into the engineered reservoir at some distance from the first well. In a properly engineered HDR reservoir, there are a number of fluid-flow pathways between the injection and production wellbores.

To operate the heat mine, a high-pressure injection pump is used to circulate water through the engineered reservoir in a closed loop as shown in Figure 1. The injection pump provides the sole motive force for moving the water continuously around the loop to mine energy from the reservoir and deliver it to a power plant on the surface. The hydraulic pressure applied via the injection pump also serves to keep the joints within the reservoir propped open[7]. The operating parameters applied to the injection pump thus greatly affect both the flow rate through the reservoir and its instantaneous fluid capacity. By using a combination of injection and production control measures, an almost limitless variety of operating scenarios may be employed to mine the heat from an HDR reservoir.

HDR Reservoir Development

Numerous hot springs and other geothermal features provide evidence of the high heat flow in the Jemez Mountains of northern New Mexico, an area dominated by the Valles Caldera, a dormant volcano. Field work to demonstrate the

HDR concept began in 1972 with heat flow and hydraulic fracturing experiments in various parts of the Jemez Mountains. In 1974, a permanent test facility was established at Fenton Hill, about 35 mi by road west of Los Alamos. The Fenton Hill site lies about 1.7 mi west of, and outside, the ring fault structure of the Valles Caldera that defines the boundary of recent (60,000 yr) resurgent volcanic activity. The basement rock at a depth of 9000 to 13,000 ft beneath the surface of Fenton Hill is composed of a highly jointed Precambrian plutonic and metamorphic complex. Other than an elevated geothermal gradient (about 3.5°F/100 ft), the only volcanic association of the reservoir rock is in the contained pore fluids which are high in dissolved carbon dioxide, and contain trace amounts of hydrogen sulfide.

While Fenton Hill was selected primarily on the basis of favorable heat flow and the lack of structural complexity in the anticipated reservoir rock, its location on a paved road made it easy to bring in heavy equipment. In addition, although the western flank of the caldera is heavily forested, a fire had destroyed much of the vegetation at the Fenton Hill site. Thus, the environmental impact of the project in this highly scenic area was small. Finally, the Fenton Hill site, as a part of the Santa Fe National Forest, was under the jurisdiction of the US Forest Service. It was therefore a simple matter to arrange an inter-governmental agreement to transfer management (but not ownership) of the land to the DOE. Los Alamos could then operate the site under its role as a contractor to the DOE. For all of these reasons, Fenton Hill appeared to be a good permanent site for carrying out HDR work.

The Phase I HDR Reservoir. Development of the world's first HDR system was initiated at Fenton Hill in 1974. The first borehole was drilled in granitic rock to a depth of 9,600 ft where the temperature was 386°F. After a series of hydraulic fracturing experiments, a second wellbore was drilled toward the largest of the near-vertical, stimulated natural joints. A good connection was not immediately achieved, and sidetracking was necessary to establish contact with the initial well via a combination of induced and natural fracture pathways.

The Phase I system was evaluated in a series of flow experiments from 1978 to 1980[8]. In the first flow test, water was circulated through the reservoir for 75 days in early 1978. The significant thermal drawdown (from 347°F to 185°F) indicated that only a small heat transfer area existed. A second 28-day test in late 1978 assessed the effects of imposing a high backpressure on the production wellbore. This strategy was found to reduce flow impedance but not to increase the surface area of heat extraction. The reservoir was then enlarged by further hydraulic fracturing and two more flow experiments were conducted: First, a flow test lasting 23 days was carried out to quantify the operating performance of the enlarged reservoir. This was followed by a 286-day heat extraction flow test during which the reservoir temperature declined from an initial value of 313°F to a final level of 300°F.

At the end of this series of flow tests, a short stress-unlocking experiment was performed. It entailed applying an elevated pressure to the reservoir in order to facilitate relative movement of joint surfaces and the resulting redistribution of fluid flow and/or the opening of new fluid pathways in the cooled reservoir rock. There were abundant indications of seismic activity within the reservoir during the pressurization experiment, and subsequent flow measurements suggested that the reservoir impedance had indeed been reduced. However, the system was not operated long enough following the stress-unlocking experiment to demonstrate that the improved flow conditions could be maintained for an extended length of time.

The pioneering work with the Phase I HDR reservoir proved that heat could be extracted from HDR using the techniques conceived and developed at Los Alamos. In addition, it indicated that issues such as induced seismicity, water consumption, and fluid geochemistry (including its effect on the system components), would not present insurmountable problems in operating an HDR heat mine. This initial field work highlighted the dynamic nature of HDR reservoirs, even under steady-state operating conditions, and laid the groundwork for the development of strategies to increase the productivity of future HDR reservoirs.

The Current HDR Reservoir. Taken together, the hydraulic fracturing operations employed to create and enlarge the Phase I HDR reservoir involved the injection of somewhat less than 70,000 cubic ft of water. The rapid cooldown of that reservoir indicated the need to create a much larger and hotter HDR reservoir in order to produce energy at the high rates and temperatures required for commercial power production. For this reason, plans were developed for a Phase II HDR reservoir which would be larger, deeper, and hotter. These plans were based on generalizations about the formation of HDR reservoirs, some of which later proved to be incorrect.

The results of work with the Phase I reservoir led to the assumption that hydraulic fracturing typically let to the formation of thin, vertical fractures in the intact rock, and that the size and heat production capability of an HDR system could be manipulated by employing a number of fracturing operations in isolated sections of a single wellbore to induce multiple, independent vertical fractures of this type. Until these preconceived notions were cast aside, extreme difficulties were encountered in the creation of a viable Phase II HDR system.

In 1980, under the auspices of the International Energy Agency, Japan and Germany joined the US HDR project. Both countries contributed funding and personnel to the project for the next five years, and the Japanese continued to be a part of the program for one additional year. Development of the Phase II system by this international group took place at the Fenton Hill Site within a few hundred ft of the Phase I wellbores. Work proceeded under the assumption that hydraulic fracturing would lead to vertical fractures as discussed above. Therefore, two wells were drilled before any fracturing was attempted. The deeper well was drilled to a vertical depth of 14,400 ft with the bottom 3,280 ft directionally drilled at an angle of 35° to the vertical. The temperature of the rock at the final depth was 621°F. The second well was drilled in a similar manner to the first, but with the inclined section located 1,250 ft vertically above the lower wellbore. The intent was to position the wellbores so that a number of individual vertical fractures, far enough apart to be thermally isolated from one another, could be created to connect the two wellbores.

A number of fracturing operations were conducted between 1982 and 1984. During the largest of these in December 1983, over 750,000 cubic ft of water (more than 10 times what was injected during all the experimental work with the Phase I system) was injected into an isolated zone of the lower wellbore located at a depth of 11,550-11,650 ft. The pumping was carried out over a period of 2-1/2 days at pressures averaging 7,000 psi. Neither this operation, nor any of the other hydraulic fracturing experiments resulted in a flow connection between the two wellbores. Furthermore, microseismic data indicated that the reservoir was developing approximately along the trajectory of the inclined portion of the lower wellbore in such a way that a connection between the two wellbores would never be established.

It was then decided to sidetrack and redrill the upper wellbore with the goal of penetrating the reservoir volume indicated by the microseismic data. Sidetracking was initiated at a depth of 9,284 ft. Drilling continued to a final depth of 13,182 ft, where a bottomhole rock temperature of 509°F was measured. The sidetracked well penetrated the reservoir and intersected a number of joints that had been opened during the large hydraulic fracturing operation described above. A small amount of additional stimulation produced good flow connections between the two wellbores. A cross-section view of the underground portion of the Phase II HDR system is shown in Figure 2.

The experience of five years of drilling, fracturing, and redrilling led to a complete change of thinking in regard to the nature of the fractures produced in HDR reservoirs. Extensive microseismic analyses and geologic evidence had indicated that the original concept of vertical flow passages created by actually forming new fractures in the basement rock was incorrect. Instead, all the evidence pointed to the opening of existing, but previously sealed, joints. As might be expected, the initial joint openings were found to occur in a direction approximately orthogonal to the least principle earth stress.

Simple geometric evidence indicates that the reservoir has a flow-connected volume of about 650 million cubic ft, and is ellipsoidal in shape, with axes ratios of approximately 3, 2, 1, respectively[9]. The longest axis tends north-south, the shortest axis lies in an approximately east-west direction, and the intermediate axis is tilted approximately 30° from the vertical. The reservoir is penetrated by two wellbores, each of which terminates in an open-hole zone approximately 1,000 ft in length. The distance between the two wellbores at the open-hole depth averages 300-500 ft.

The Fenton Hill Surface Plant. Between 1987 and 1991, a surface plant, designed to meet power-industry standards and capable of extended operation, was constructed and mated to the large HDR reservoir. Figure 3 shows the principle components of the surface plant. The heart of the surface plant is the injection pump which supplies the motive force for moving the fluid through the circulation loop. Originally, two diesel-powered reciprocating injection pumps were installed in the surface plant. These were designed for use on an alternating schedule, with one pump in operation and the other in reserve at any point in time. The pumps could be adjusted for operation over a wide range of pressures and flow rates. Each was capable of injecting a maximum volume of about 175 gpm of water at pressures as high as 5,000 psi. For reasons unrelated to HDR technology, both these pumps failed within a span of two days during a period of normal operations. Several months of intermittent operations passed before a rented centrifugal pump powered by electricity was installed in the system. While lacking operational flexibility, the electric pump was extremely simple and very reliable. This original centrifugal pump was returned to its owner in late May 1993. A pump of similar design but with a somewhat higher flow capacity was subsequently purchased and installed permanently at Fenton Hill when the decision was made to resume flow testing in 1995.

The injection pump, piping to the injection wellhead, both wellheads, the wellbores and all flow paths through the reservoir constitute the high pressure portion of the circulation loop. This part of the system has been built for operation at applied surface pressures of up to 5,000 psi. The remainder of the loop, the low pressure side, includes a particle/gas separator, an air-cooled heat exchanger, a makeup water pump, and connecting piping. This part of the system is capable of operation at up to 1000 psi. It feeds directly back to the injection pump. The surface plant is designed for automated operation and instrumented for measurement of fluid temperature, flow, and pressure at numerous points in the loop[10].

Initial Flow Testing of the Large Fenton Hill HDR Reservoir. After several preliminary experiments, a 30-day, closed-loop flow test of the Phase II HDR reservoir was carried out in mid-1986[11]. This test was run at two injection pressures, 3,900 and 4,500 psi. Pumping rates at these two pressures were typically 168 and 295 gpm, respectively. While about 40 microearthquakes were detected during the lower pressure part of the test, several hundred microseismic events were observed when the pressure was raised to the higher level. These microearthquakes occurred almost exclusively on the side of the reservoir away from the production well. In other words, reservoir growth appeared to take place in that portion of the reservoir which was isolated from the pressure relief provided by the production wellbore. On the surface, the production side of the loop was maintained at a pressure of about 500 psi to prevent boiling of the superheated water or escape of the gases (principally carbon dioxide) dissolved in the circulating fluid.

This initial test was of short duration, and was run with improvised surface equipment. In addition, the flow was interrupted a number of times during the 30-day test period. While this test did not generate data that could be used to demonstrate the routine operation of an HDR reservoir because steady-state operating conditions were never definitively established, it did show that the two wellbores penetrating the large reservoir were well-connected and that energy could be produced from the large HDR reservoir at significant rates.

Long Term Production Flow Testing

Goals and Design. Over the past several years a series of flow tests of the large HDR reservoir has been conducted. During 1992-1993 a long-term flow test (LTFT) program was carried out to demonstrate that the Phase II HDR reservoir at Fenton Hill and, by implication, HDR reservoirs in general could be operated on a continuous basis to produce useful amounts of energy over extended periods of time. The LTFT was designed to obtain information about the expected thermal lifetime of the Fenton Hill HDR reservoir, water consumption, operating and maintenance costs, and the geophysical, geochemical and environmental effects of long-term operation of an HDR system.

As a result of intensive discussions with the HDR Program Industrial Advisory Group, the LTFT was conducted under conditions simulating as closely as possible the operation of a commercial HDR power plant. The pressure under which water was pumped into the injection wellbore was adjusted to the highest level that could be maintained without leading to expansion of the reservoir volume, as indicated by the onset of microseismic activity and an increased rate of water consumption. Experience had shown that for the Fenton Hill reservoir this pressure was just under 4,000 psi.

Upon the close of the LTFT, special flow testing was continued for several additional weeks to investigate techniques to improve the productivity of the large HDR reservoir[12]. The reservoir was then placed on standby status for two years. In May 1995, circulation through the reservoir was resumed in the form of reservoir verification testing. The purpose of this most recent flow testing program was to ascertain the condition of the HDR reservoir after two years of dormancy, to demonstrate that the steady-state operating conditions of the LTFT test period could be re-established, and to further explore methods for maximizing the productivity of the system at Fenton Hill.

Test Operations. During the LTFT and all subsequent testing, water was generally injected in the reservoir at a surface pressure of 3,960 psi. A backpressure of 1,400 psi was typically maintained on the production wellhead in order to prop open, by means of this imposed pressure, the fluid-carrying joints in the relatively low-pressure region of the reservoir immediately adjacent to the outlet into the production wellbore. The system pressure was reduced to about 700 psi at the outlet of the production wellhead, and this pressure was maintained until the water was returned to the injection pump for repressurization and reinjection into the reservoir. The plant was computer-controlled, with fluid circulation maintained 24 hours a day under these constant operating conditions. For much of the test period, the facility was manned only during daylight hours. On a number of occasions, usually as a result of power failures caused by local weather conditions, the plant went into an automatic shutdown mode. The plant was then re-started either by an operator called in especially for that purpose or when the operating staff routinely arrived the next morning.

Important system parameters such as pressure, temperature, and flow rate were monitored continuously. Measurements of the geochemistry of the circulating fluid were made several times a week. Finally, diagnostic procedures such as production-well temperature logging and tracer analyses were implemented every few weeks or at critical junctures in the test program.

Continuous operation of the LTFT began on April 8, 1992, and proceeded with only minor interruptions for 112 days. Catastrophic failures of both reciprocal injection pumps within a two-day period forced suspension of testing on July 31. Although the pump failures were not related to HDR technology, the ensuing lapse in testing while suitable replacement pumping capacity was being evaluated, procured, and installed, was a serious setback to the LTFT effort. By mid-February 1993, a replacement pump was in place at Fenton Hill and a second continuous phase of flow testing was begun. The new pump was a leased centrifugal unit powered by electricity. Once the appropriate modifications to the electric power supply at the site had been implemented, it proved to be highly reliable. The second continuous test period ran for 55 days until mid-April 1993, when the available funding was exhausted. The two steady-state periods of the LTFT were subsequently designated LTFT Phase 1 and LTFT Phase 2, respectively.

At the end of the formal LTFT, a five-day period of cyclic flow operations was initiated in an attempt to obtain additional insight into factors affecting the operation of an HDR reservoir. The test was made possible only because the pump manufacturer extended the lease on the pump for an additional month at a highly favorable rate. In an initial cyclic test completed a few months earlier, the production wellbore had been briefly shut in each morning. That test had shown a favorable impact on overall system productivity[13]. The subsequent five-day cyclic test entailed a much longer production shut-in period. While injection continued around the clock, production was maintained for only eight hours a day. On the morning of the third production cycle of this test, a sudden and unanticipated increase of about 48% in the production flow rate was observed. Because of the significance of this sudden flow increase, the cyclic operational schedule was terminated and the reservoir was brought into steady-state operations for an additional 17 days to evaluate this effect under well-understood operating conditions.

As mentioned above, the HDR system at Fenton Hill was shut in for two years upon the termination of flow testing in May 1993. In May 1995, operations were resumed using a new pump of centrifugal design built especially for the project by REDA Pump Company of Bartlesville, OK. The operational control pressures in effect during the LTFT were emulated in the initial stages of the reservoir verification testing program of 1995. As this paper is being written, the 1995 test program is still in progress.

Flow Test Results. Table 1 summarizes typical operating parameters during the two LTFT phases, the period after the sudden flow increase in May 1993, and after about a month of circulation during the reservoir verification testing of 1995.

The data of Table 1 show typical values for the test periods represented in each column, and provide important insights into the operation of HDR energy extraction systems. First and perhaps foremost, the production temperatures of the circulating fluid remained consistently in the same range during all the flow testing. The small temperature variations among the data shown in the table closely correlate with differences in flow rates, and can be attributed to varying rates of energy loss to the rock surrounding the production wellbore as the fluid traveled the two-mile distance up the production wellbore from the reservoir to the surface. Logging data collected on a number of occasions showed essentially no change in the temperature of the fluid at the point where it entered the cased portion of the production wellbore.

Water loss data also showed consistent trends. High reservoir pressures were maintained over the span of the LTFT, including the interim period between the two steady-state phases of the test. In the face of the sustained application of a constant high pressure on the reservoir, water losses continually declined as the pressurization of the microcracks in the rock at the periphery of the reservoir proceeded. Just after the close of the LTFT, at the time of the flow increase, injection was being continuously maintained while production was intermittent. This operating regimen resulted in excess water storage so that, as indicated in Table 1, no real water loss numbers could be determined.

The reservoir verification flow testing of 1995 was initiated after a period of two years during which the pressure on the reservoir had been allowed to decay to a relatively low level of 1,450 psi, and then maintained at this level. During that two-year period, water flowed back into the reservoir from the overpressured region in the surrounding rock. Thus at the start of the 1995 flow test, the reservoir and surrounding rock conditions were similar to those at the start of the LTFT. It is expected that water losses during the period of reservoir verification testing will show the same long-term downward trend as that observed during the LTFT.

In all the cases illustrated, the injection pressure and the production-wellhead backpressure were the primary control points. The injection and production flow rates, which are direct functions of these applied pressures, were extremely stable during the two phases of the LTFT in spite of the fact that these test periods were separated by a six-month period of low-flow, sporadic circulation. As mentioned above, the flow-increase event occurred during a period of cyclic testing, when injection was maintained on a continuous basis while production was shut-in for 16-hour periods. Under such conditions, it is reasonable to expect significant increases in reservoir pressure levels in the vicinity of the production wellbore, which acts as a pressure relief valve when it is open, but not, of course, when it is shut-in. It appears that, under the elevated pressure conditions induced in that part of the reservoir during the cyclic operations, a new major pathway through the reservoir may have suddenly been opened. This phenomenon offers some intriguing possibilities in reservoir management and operations if it can be repeated and more fully understood.

The flow rates observed upon the resumption of testing in 1995, indicated that some residual effects of the sudden flow-increase event persisted even after two years of reservoir dormancy. The most obvious process expected to occur during a long period of reservoir shut-in, is temperature recovery at the surfaces of open joints within the reservoir. It thus appears at this time that localized reservoir temperature profiles may have played an important role in the initiation of the sudden flow increase and in its subsequent mitigation. Additional, well-designed, flow experiments are required, however, if the effects of pressure, localized temperature, and other factors that may have led to some of the surprising production patterns observed since the close of the LTFT are to be fully understood.

The Prospects for Further HDR Technology Development

Over the past few years, a number of important questions about HDR technology have been answered. It is clear that HDR facilities can be highly automated and operated routinely in a manner that makes them amenable to routine energy production. The energy required to operate the plant has been shown to be but a fraction of that produced. Water consumption can be kept within reasonable bounds during such routine operation. In fact, both the flow test results discussed above and earlier static testing have indicated that water use should decline to very low levels when a plant is operated over an extended period of time. At least at the Fenton Hill facility, the simple geochemistry and relatively neutral character of the fluid circulating in the closed loop shows promise of facilities that can be operated with minimal maintenance. Finally, the environmental advantages of the closed-loop circulation process were clearly demonstrated by the absence of any emissions during flow testing.

The principal remaining questions are concerned primarily with thermal performance over the extremely long times required for commercial power plant applications (which may be 20-30 years) and productivity sufficient to make commercial applications viable. These questions may best be addressed by an approach that involves operation of an HDR facility in a commercial setting.

A Government Cost-Shared, Industry-Led HDR Project. Upon the close of the LTFT in 1993, a plan was formulated to address the remaining issues of reservoir thermal longevity and net system productivity by bringing American industry into the HDR program. In early September 1993, based in part on the test results described in this paper, the DOE formally asked for input from US private industry in regard to the formation of a joint industry/government project to develop a facility to produce and market energy derived from an HDR resource. A total of 41 responses were received. About 30 of the organizations responding expressed an interest in actively participating in the proposed program.

In the early summer of 1994, the Director of the DOE Geothermal Division, in a memorandum to the DOE's Albuquerque Operations Office located in Albuquerque, New Mexico, authorized the preparation of a formal solicitation seeking industrial partners in a project that would involve "...constructing a prototype facility to produce and market electric power or heat generated from geothermal energy in hot dry rock." The memo further stated that the DOE's 1995 budget would include at least $2 million for the project, and requested that the solicitation be issued sometime during August-September 1994, for implementation in the 1995 Fiscal Year.

The prospective project is envisioned as a staged, multi-year effort that will be carried out by a team consisting of a resource owner, a project developer, a plant operator and a customer for the energy. The industry team will specify the site, design and construct the facility to extract energy from the HDR resource, operate the plant, and deliver the energy to the customer. If the project entails electric power production, as seems most likely, the team will be responsible for designing and operating the power plant for converting the thermal energy to electricity.

The DOE will contribute up to 50% of the installation cost (up to a maximum of $30 million) of the HDR energy production and marketing facility. The DOE will also provide an additional $1.5 million per year in "reservoir verification support" funding, for the first three years that the facility operates to produce and market power. The private development team will finance the balance of the project. It is expected that with this significant degree of government participation, an HDR facility can be constructed that will market energy at a competitive rate, pay its own operating expenses, and return a profit commensurate with the risks and opportunities involved.

It is anticipated that the industry-led HDR project will address the major remaining technical issues associated with HDR, including capital construction cost for HDR systems, reservoir thermal productivity, and lifetime. One goal will be to design and construct the facility as a production plant rather than a research facility in order to obtain the actual experience base needed to back up the numerous paper economic studies of capital construction costs of HDR systems. It is essential that the project generate sufficient revenue to pay its operating costs in order to assure that the plant will continue to run over the long term, thereby providing the long-term reservoir thermal data so important to making HDR a credible commercial source of energy. To achieve competitive operational costs, it will be essential to apply the most up-to-date technical concepts of HDR reservoir engineering and to design the reservoir for maximum sustainable productivity.

The industry-led project may be implemented either at the current Fenton Hill HDR site or at a new location. Because a significant HDR infrastructure, including wellbores and a high-quality reservoir, already exists at Fenton Hill, it is an attractive candidate for a power producing and marketing facility. At present, however, the HDR system there cannot produce energy at a rate high enough to make a marketing effort practical. Increased power capacity achieved by drilling another production well, would be a necessary part of any power production and energy marketing plan at Fenton Hill. In the final analysis, the selection of the site for the industry-led project will be determined by a combination of factors, including resource, environmental, transmission, and customer considerations.

The formal solicitation process began when the solicitation notice was published in the Commerce Business Daily on December 28, 1994. The bidding process closed in late April 1995, and by the end of June 1995, the process of selecting the successful applicant was well underway. It was anticipated that an award would be granted before the end of the federal fiscal year on September 30, 1995.

Future applications of HDR Technology. The initiation of the industry-led project in 1995, will set the course for the commercialization of HDR technology before the turn of the century. After preliminary site and permitting work in 1996, it should be possible to carry out drilling and reservoir development in 1997, conduct flow testing and construct a surface plant in 1998, and bring the jointly financed plant on-line in 1999.

As the first industrial HDR plant operates and proves that HDR technology can be commercially competitive, the prospects for the development of additional HDR power production facilities will grow. The economic and social benefits of the additional applications of HDR, such as production of thermal energy for direct use in low-grade resource locations, or water purification in conjunction with energy production will then become increasingly apparent. More esoteric applications of the technology may also become feasible, including the utilization of a deep HDR resource to generate steam for use in enhanced oil recovery from a co-located, but shallower, petroleum reservoir, or even the synthesis of exotic chemical compounds in an HDR reservoir used as a chemical reactor.

As experience leads to improvements in the technical understanding of HDR reservoirs, and advanced HDR facilities are designed and constructed, the competitive position of the technology will be enhanced. When HDR technology matures in the 21st century, it will command a significant share of the worldwide energy market, and may serve mankind in a variety of other ways as well.

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